Received: 09 February 2025 / Accepted: 10 May 2025 / Published online: 30 June 2025

DOI 10.34689/SH.2025.27.3.011

UDC 579.842.16:615.33.

ANALYSIS OF ANTIBIOTIC SUSCEPTIBILITY AND RESISTANCE OF KLEBSIELLA PNEUMONIAE IN VARIOUS BIOLOGICAL MATERIALS

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Abstract

Background: Antibiotic resistance of Klebsiella pneumoniae remains one of the most pressing issues in clinical microbiology and healthcare. With the active spread of multidrug-resistant strains, especially in hospital settings, the need for local monitoring of antibiotic susceptibility is becoming increasingly urgent to ensure effective treatment selection.

Objective: To assess the susceptibility and resistance of K. pneumoniae isolated from various biological materials to a broad spectrum of antibiotics and to identify the most effective drugs for empirical therapy.

Materials and Methods: The study utilized retrospective laboratory data from 169 clinical isolates of Klebsiella pneumoniae, obtained from five types of biological materials: sputum (n=65), ENT samples (n=45), urine (n=45), cerebrospinal fluid (n=9), and wound exudate (n=5). The analysis included 15 antibiotics from different classes, including cephalosporins, carbapenems, fluoroquinolones, aminoglycosides, and others. Susceptibility and resistance percentages were calculated using standard formulas. Microsoft Excel was used for primary data processing, and IBM SPSS Statistics was employed for descriptive statistical analysis.

Results: The highest susceptibility rates were observed for Imipenem (84.5%), Minocycline (82.4%), and Amikacin (79.6%), with resistance levels remaining below 20%, confirming their high efficacy against K. pneumoniae. Moderate activity was shown by Piperacillin, Cefepime, and Meropenem (approximately 70% susceptibility). In contrast, Nitrofurantoin, Cefazolin, and Trimethoprim showed the lowest activity, with resistance reaching up to 60% in some sample types. Differences in susceptibility profiles were noted depending on the biological material, although overall trends were consistent.

Conclusion: The findings underscore the importance of systematic local monitoring of K. pneumoniae antibiotic susceptibility, particularly in the context of widespread resistant strains. Imipenem, Minocycline, and Amikacin may be considered first-line agents for empirical treatment of K. pneumoniae infections. The reduced efficacy of several traditional antibiotics also highlights the need for cautious use in clinical practice.

Keywords: *Klebsiella pneumoniae, antibiotic resistance, susceptibility, resistance, biological materials.*

For citation:

Mukasheva G.D., Maukayeva S.B., Kudaibergenova N.K., Shabdarbayeva D.M., Smailova Zh.K., Tokayeva A.Z., Smail Y.M., Nuralinova G.I., Issabekova Zh.B., Karimova S.S., Kozubayeva D.B., Goremykina M.V., Urazalina N.M. Analysis of antibiotic susceptibility and resistance of Klebsiella Pneumoniae in various biological materials // *Nauka i Zdravookhranenie* [Science & Healthcare]. 2025. Vol.27 (3), pp. 98-107. *doi 10.34689/SH.2025.27.3.011*

Резюме

АНАЛИЗ ЧУВСТВИТЕЛЬНОСТИ И УСТОЙЧИВОСТИ KLEBSIELLA PNEUMONIAE К АНТИБИОТИКАМ В РАЗЛИЧНЫХ БИОМАТЕРИАЛАХ

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Введение: Антибиотикорезистентность Klebsiella pneumoniae продолжает оставаться одной из наиболее актуальных проблем клинической микробиологии и здравоохранения. В условиях активного распространения мультирезистентных штаммов, особенно в стационарах, возрастает необходимость в локальном мониторинге чувствительности к антибактериальным препаратам для эффективного подбора терапии.

Цель: Оценить уровень чувствительности и устойчивости K. pneumoniae, выделенной из различных биологических материалов, к широкому спектру антибиотиков и определить наиболее эффективные препараты для эмпирического лечения.

Материалы и методы: В исследование включены ретроспективные лабораторные данные по 169 клиническим изолятам Klebsiella pneumoniae, полученным из пяти типов биоматериалов: мокрота (n=65), ЛОР-материалы (n=45), моча (n=45), церебральный канал (n=9), рана (n=5). Анализ включал 15 антибиотиков различных групп, в том числе цефалоспорины, карбапенемы, фторхинолоны, аминогликозиды и другие. Расчёт процентных показателей чувствительности и устойчивости проводился по стандартным формулам, с применением Microsoft Excel для первичной обработки данных и IBM SPSS Statistics — для статистического анализа.

Результаты: Максимальные уровни чувствительности выявлены у Imipenem (84,5%), Minocycline (82,4%) и Amikacin (79,6%), при минимальных показателях устойчивости (<20%), что подтверждает их высокую эффективность против K. pneumoniae. Умеренные показатели продемонстрировали Piperacillin, Cefepime и Meropenem (чувствительность около 70%). В то же время, наименьшая активность отмечена у Nitrofurantoin, Cefazolin и Trimethoprim, устойчивость к которым в отдельных материалах достигала 60%. Заметны отличия в профиле чувствительности в зависимости от биологического материала, однако общие тенденции сохраняются.

Вывод: Результаты подчёркивают необходимость систематического локального мониторинга антибиотикочувствительности K. pneumoniae, особенно в условиях высокой распространённости устойчивых штаммов. Imipenem, Minocycline и Amikacin могут рассматриваться в качестве препаратов первой линии при эмпирическом лечении инфекций, вызванных данным патогеном. Полученные данные также свидетельствуют о сниженной эффективности ряда традиционных препаратов, что требует осторожного подхода к их применению.

Ключевые слова: *Klebsiella pneumoniae, антибиотикорезистентность, чувствительность, устойчивость, биоматериалы.*

Для цитирования:

Мукашева Г.Д., Маукаева С.Б., Кудайбергенова Н.К., Шабдарбаева Д.М., Смаилова Ж.К., Токаева А.З., Смаил Е.М., Нуралинова Г.И., Исабекова Ж.Б., Каримова С.С., Козубаева Д.Б., Горемыкина М.В., Уразалина Н.М. Анализ чувствительности и устойчивости Klebsiella Pneumoniae к антибиотикам в различных биоматериалах // Наука и Здравоохранение. 2025. Т.27 (3), С. 98-107. doi: 10.34689/SH.2025.27.3.011

Түйіндеме

KLEBSIELLA PNEUMONIAE-НІҢ ӘРТҮРЛІ БИОЛОГИЯЛЫҚ МАТЕРИАЛДАРДАҒЫ АНТИБИОТИКТЕРГЕ СЕЗІМТАЛДЫҒЫ МЕН ТӨЗІМДІЛІГІН ТАЛДАУ

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Кіріспе: Klebsiella pneumoniae бактериясының антибиотиктерге төзімділігі клиникалық микробиология мен денсаулық сақтау саласындағы ең өзекті мәселелердің бірі болып қалып отыр. Ауруханаларда мультирезистентті штаммдардың кең таралуы тиімді емдеу әдістерін таңдауда жергілікті деңгейде антибиотиктерге сезімталдықты бақылаудың маңыздылығын арттырады.

Мақсаты: K. pneumoniae штаммдарының әртүрлі биологиялық материалдардан бөлініп алынған жағдайларында антибиотиктерге сезімталдық және төзімділік деңгейін бағалау, сондай-ақ эмпирикалық емдеу үшін ең тиімді препараттарды анықтау.

Материалдар мен әдістер: Зерттеу аясында 169 клиникалық Klebsiella pneumoniae изоляттарына қатысты ретроспективті зертханалық деректер пайдаланылды. Биоматериалдар мынадай бес топтан алынды: қақырық (n=65), ЛОР-мүшелерінен алынған материалдар (n=45), несеп (n=45), ми-жұлын сұйықтығы (n=9), жара іріңі (n=5). Зерттеу 15 антибиотикті қамтыды: цефалоспориндер, карбапенемдер, фторхинолондар, аминогликозидтер және басқа топтар. Антибиотикке сезімталдық пен төзімділіктің пайыздық көрсеткіштері стандартты формулалар бойынша есептелді. Деректер Microsoft Excel арқылы өңделіп, статистикалық талдау үшін IBM SPSS Statistics бағдарламасы қолданылды.

Нәтижелер: Ең жоғары сезімталдық Imipenem (84,5%), Minocycline (82,4%) және Amikacin (79,6%) антибиотиктерінде байқалды, ал төзімділік деңгейі 20%-дан төмен болды. Piperacillin, Cefepime және Meropenem препараттары орташа белсенділік көрсетті (шамамен 70%). Ал Nitrofurantoin, Cefazolin және Trimethoprim сияқты антибиотиктер төмен белсенділік көрсетті, кейбір материалдарда төзімділік деңгейі 60%-ға дейін жетті. Биоматериал түріне байланысты сезімталдық профилінде айырмашылықтар болғанымен, жалпы үрдістер сақталды.

Қорытынды: K. pneumoniae штаммдарының антибиотикке сезімталдығын жергілікті деңгейде жүйелі түрде бақылау аса маңызды, әсіресе резистентті штаммдардың таралуы жоғары болған жағдайда. Imipenem, Minocycline және Amikacin препараттары эмпирикалық емдеу үшін бірінші таңдаулы дәрілер ретінде қолдануға ұсынылады. Кейбір дәстүрлі антибиотиктердің тиімділігінің төмендеуі оларды қолдануда сақтықты талап етеді.

Кілт сөздер: *Klebsiella pneumoniae, антибиотиктерге төзімділік, сезімталдық, биоматериалдар.*

Дәйексөз үшін:

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Introduction

Klebsiella pneumoniae ranks among the leading causative agents of hospital-acquired infections and poses a serious threat to immunocompromised patients. In the context of the global rise in antibiotic resistance, the situation involving K. pneumoniae isolates resistant to carbapenems and third-generation cephalosporins is particularly alarming. These strains are increasingly detected in various types of biological materials such as blood, urine, sputum, and exudates, complicating the selection of effective empirical therapy [18].

An analysis of antibiotic susceptibility in strains isolated from different biological sources reveals significant variations in resistance profiles. For example, strains obtained from wounds and blood of patients with orthopedic infections often produce carbapenemases and exhibit multidrug resistance, including resistance to fluoroquinolones and aminoglycosides [4]. A similar situation is observed in dialysis and transplant facilities, where strains from urine and vascular catheters show high resistance to β-lactam antibiotics [10].

Particular attention should be given to strains isolated from children with cystic fibrosis: under constant colonization pressure from K. pneumoniae, unique mechanisms of adaptation and resistance to antimicrobial agents are formed [18]. In addition, patients with tuberculosis, who are frequently subjected to prolonged antibiotic therapy, demonstrate plasmid-mediated resistance mechanisms to broad-spectrum drugs [11].

Based on accumulated clinical data, it can be concluded that the resistance spectrum of K. pneumoniae is directly related to the infection site. For instance, strains isolated from bronchoalveolar lavage and lower respiratory tract aspirates often produce extended-spectrum β-lactamases, whereas those from urine tend to exhibit resistance to fluoroquinolones and nitrofurans [20]. Additional microbiological analysis of aspirates, punctates, and pleural exudates has shown a high frequency of isolation of multidrug-resistant strains with marked resistance to third-generation cephalosporins and carbapenems [17]. Particularly concerning data have been reported regarding oncohematological patients, in whom Klebsiella pneumoniae is found in virtually all types of biological materials from blood and aspirates to punctates and feces [5].

Modern approaches to assessing Klebsiella pneumoniae resistance involve not only phenotypic methods but also molecular-genetic characterization. For example, Gordinskaya and Boriskina demonstrated that isolates from different hospitals vary significantly in the presence of carbapenemase genes (e.g., KPC, NDM), as well as in resistance mechanisms to colistin, especially in aspirate and bronchoalveolar lavage samples [9].

Analysis of hypermucoid strains isolated from wound exudates revealed their increased resistance to cephalosporins and aminoglycosides, which may be related to capsular factors and biofilm formation [13]. These properties significantly reduce the effectiveness of traditional treatment regimens.

Belkova N.L. et al. conducted a comparative genomic analysis of isolates obtained from blood, urine, and exudates, demonstrating the presence of mutations encoding resistance to novel beta-lactam antibiotics [3]. Another study revealed that K. pneumoniae isolates from trauma units more frequently exhibit polyresistance, especially in aspirates and purulent discharges [7].

To date, the diagnosis and treatment of infections caused by K. pneumoniae require not only awareness of general antibiotic resistance trends but also an understanding of the microbiological characteristics specific to each type of biological material. Integrating data from various sources allows for a more accurate analysis of antimicrobial susceptibility, which in turn supports the development of effective treatment strategies.

The aim of the study is to analyze the antibiotic susceptibility and resistance of Klebsiella pneumoniae isolated from different biological materials, in order to identify specific features of antimicrobial resistance depending on the source of the clinical isolate.

Materials and methods

The study utilized retrospective laboratory data on the antibiotic susceptibility of *Klebsiella pneumoniae* to various antimicrobial agents. The biological samples used for bacteriological analysis included sputum (n = 65), ENT materials (n = 45), urine (n = 45), cerebrospinal fluid (n = 9), and wound exudate (n = 5). The analysis included 15 antibiotics, among them: Ceftriaxone, Cefazolin, Cefuroxime, Cefepime, Piperacillin, Minocycline, Imipenem, Levofloxacin, Nitrofurantoin, Ceftriaxidime, Meropenem, Tobramycin, Amikacin, and Trimethoprim.

For quantitative analysis, relative susceptibility and resistance were calculated for each antibiotic based on the biological material tested.

The following formulas were used:

1) Susceptibility = (Number of susceptible isolates / Total number of isolates for the material) × 100

2) Resistance = (Number of resistant isolates / Total number of isolates for the material) × 100

Data were entered into Microsoft Excel for initial sorting and calculation of susceptibility and resistance percentages. Statistical analysis was performed using IBM SPSS Statistics, applying descriptive statistical methods.

Results

Table 1 presents the number of Klebsiella pneumoniae strains identified as either susceptible or resistant to antibiotics across five types of biological materials: sputum, ENT organs, urine, cerebrospinal fluid, and wound samples. The highest number of isolates was obtained from sputum (65) and ENT materials (45), while significantly fewer strains were isolated from cerebrospinal fluid (9) and wounds (5). The susceptibility analysis showed that antibiotics such as Piperacillin and Imipenem demonstrated high levels of susceptibility across all sample types, particularly in sputum and ENT materials. Conversely, Cefazolin and Nitrofurantoin showed higher levels of resistance, indicating limited effectiveness of these drugs in treating infections caused by K. pneumoniae.

Table 2 presents the percentage of Klebsiella pneumoniae susceptibility to various antibiotics depending on the type of biological material: sputum, ENT organs, urine, cerebral canal, and wound. The highest levels of susceptibility were observed for the antibiotics Minocycline and Imipenem, which showed consistently strong results exceeding 85% across all sample types, including sputum and urine. Piperacillin also demonstrated high susceptibility, particularly in urine (88%) and sputum (81.5%). Cefepime, Cefuroxime, and Levofloxacin were characterized by moderately high susceptibility levels (ranging from 60% to 80%) across all studied biological materials. In contrast, Nitrofurantoin and Trimethoprim showed lower susceptibility rates, not exceeding 55% in most sample types, indicating their limited effectiveness in treating infections caused by Klebsiella pneumoniae.

Table 1.

Number of susceptible and resistant Klebsiella pneumoniae isolates by sample type.

Antibiotic	Sputum (65)		ENT Organs (45)		Urine (45)		Cerebral Canal (9)		Wound (5)	
	Sus	Res	Sus	Res	Sus	Res	Sus	Res	Sus	Res
Ceftriaxone	42	23	27	18	28	17	6	3	3	2
Cefazolin	35	30	23	22	21	24	5	4	2	3
Cefuroxime	47	18	32	13	31	14	6	3	4	1
Cefepime	51	14	31	14	33	12	7	2	3	2
Piperacillin	53	12	41	4	40	5	7	2	4	1
Minocycline	60	5	39	6	41	4	8	1	4	1
Imipenem	61	4	40	5	42	3	8	1	4	1
Levofloxacin	50	15	31	14	38	7	7	2	3	2
Nitrofurantoin	32	33	22	23	22	23	4	5	2	3
Ceftrazidime	48	17	22	23	37	8	6	3	2	3
Meropenem	43	22	37	8	38	7	6	3	4	1
Tobramycin	37	28	24	21	24	21	4	5	3	2
Amikacin	57	8	39	6	35	10	7	2	4	1
Trimethoprim	34	31	24	21	23	22	5	4	3	2

Table 2.

Percentage of Klebsiella pneumoniae Susceptibility to Antibiotics.

Antibiotic	Sputum (%)	ENT Organs (%)	Urine (%)	Cerebral Canal (%)	Wound (%)
Ceftriaxone	64.6	60.0	62.2	66.7	60.0
Cefazolin	53.6	51.7	46.6	55.6	57.1
Cefuroxime	72.5	71.1	68.9	66.7	80.0
Cefepime	78.0	68.9	73.3	77.8	60.0
Piperacillin	81.5	63.2	88.0	77.8	80.0
Minocycline	92.3	86.7	91.1	88.9	80.0
Imipenem	93.8	88.9	93.3	88.9	80.0
Levofloxacin	76.9	68.9	84.4	77.8	60.0
Nitrofurantoin	49.3	48.0	48.0	44.4	40.0
Ceftrazidime	73.7	48.9	82.1	66.7	66.7
Meropenem	66.0	82.1	84.0	66.7	80.0
Tobramycin	56.6	53.3	53.3	44.4	60.0
Amikacin	87.7	86.7	77.8	77.8	80.0
Trimethoprim	52.3	53.3	50.0	55.6	60.0

Table 3 shows the percentage of resistance of Klebsiella pneumoniae to various antibiotics depending on the type of biological material: sputum, ENT organs, urine, cerebral canal, and wound. The highest resistance rates are observed for the antibiotics Cefepime, Ceftriaxone, and Piperacillin, especially in sputum and urine, where resistance levels reach 20–46%. Minocycline and Imipenem exhibit low resistance rates (from 6 to 20%) across all samples, confirming their high effectiveness. There is also a high resistance to Nitrofurantoin and Trimethoprim, ranging from 40–60%, indicating the limited clinical applicability of these drugs against Klebsiella pneumoniae.

Table 3.

Percentage of Klebsiella pneumoniae resistance to antibiotics.

Antibiotic	Sputum (%)	ENT Organs (%)	Urine (%)	Cerebral Canal (%)	Wound (%)
Ceftriaxone	35.4	40.0	37.8	33.3	40.0
Cefazolin	46.4	48.3	53.4	44.4	42.9
Cefuroxime	27.5	28.9	31.1	33.3	20.0
Cefepime	22.0	31.1	26.7	22.2	40.0
Piperacillin	18.5	36.8	12.0	22.2	20.0
Minocycline	7.7	13.3	8.9	11.1	20.0
Imipenem	6.2	11.1	6.7	11.1	20.0
Levofloxacin	23.1	31.1	15.6	22.2	40.0
Nitrofurantoin	50.7	52.0	52.0	55.6	60.0
Ceftrazidime	26.3	51.1	17.9	33.3	33.3
Meropenem	34.0	17.9	16.0	33.3	20.0
Tobramycin	43.4	46.7	46.7	55.6	40.0
Amikacin	12.3	13.3	22.2	22.2	20.0
Trimethoprim	47.7	46.7	50.0	44.4	40.0

Table 4 presents the average sensitivity and resistance rates of Klebsiella pneumoniae to various antibiotics, calculated based on data from different biological materials.

Table 4.

Comparison of Average Sensitivity and Resistance Values by Antibiotic

Antibiotic	Average Sensitivity Percentage (%)	Average Resistance Percentage (%)
Ceftriaxone	60.2	39.8
Cefazolin	54.2	45.8
Cefuroxime	64.6	35.4
Cefepime	71.1	28.9
Piperacillin	70.2	29.8
Minocycline	82.4	17.6
Imipenem	84.5	15.5
Levofloxacin	69.8	30.2
Nitrofurantoin	54.8	45.2
Ceftrazidime	67.3	32.7
Meropenem	70.4	29.6
Tobramycin	58.0	42.0
Amikacin	79.6	20.4
Trimethoprim	55.1	44.9

The highest sensitivity rates were observed for Imipenem (84.5%), Minocycline (82.4%), and Amikacin (79.6%), indicating the high effectiveness of these drugs against the studied strains. Antibiotics such as Cefepime, Piperacillin, and Meropenem also demonstrated relatively high sensitivity levels around 70%. At the same time, Nitrofurantoin, Cefazolin, Trimethoprim, and Tobramycin showed lower sensitivity rates (approximately 54–58%) and correspondingly high resistance rates (ranging from 42% to 45%), indicating limited clinical efficacy of these agents.

Table 5 presents the five antibiotics that demonstrated the highest levels of sensitivity of Klebsiella pneumoniae depending on the type of biological material: sputum, ENT organs, urine, cerebral canal, and wounds. Imipenem holds the leading position in sensitivity across all tested samples, with rates ranging from 80% (wound) to 93.8% (sputum), confirming its high effectiveness against K. pneumoniae. Minocycline and Amikacin also show consistently high results, ranking second and third respectively, with sensitivity ranging from 77.8% to 92.3%.

Piperacillin demonstrates high sensitivity levels, especially in urine and ENT samples, where it reaches over 88%. Cefepime ranks fifth for most materials, except for wound exudates, where Cefuroxime takes the fifth position with a sensitivity rate of 80%.

Table 5.

Distribution of antibiotics with the highest sensitivity levels of Klebsiella pneumoniae by biological material

Biological Material	1st Place	2nd Place	3rd Place	4th Place	5th Place
Sputum (n=65)	Imipenem (93.8%)	Minocycline (92.3%)	Amikacin (87.7%)	Piperacillin (81.5%)	Cefepime (78.5%)
ENT Organs (n=45)	Imipenem (88.9%)	Minocycline (86.7%)	Amikacin (86.7%)	Piperacillin (91.1%)	Cefepime (68.9%)
Urine (n=45)	Imipenem (93.3%)	Minocycline (91.1%)	Piperacillin (88.9%)	Amikacin (77.8%)	Cefepime (73.3%)
Cerebral Canal (n=9)	Imipenem (88.9%)	Minocycline (88.9%)	Amikacin (77.8%)	Piperacillin (77.8%)	Cefepime (77.8%)
Wound (n=5)	Imipenem (80.0%)	Minocycline (80.0%)	Amikacin (80.0%)	Piperacillin (80.0%)	Cefuroxime (80.0%)

Discussion

Among the antibiotics studied, Imipenem, Minocycline, and Amikacin demonstrated the highest activity, with resistance rates generally not exceeding 20%. These drugs showed consistently high sensitivity levels (>80%) regardless of the biological material, making them potential first-line agents for the treatment of infections caused by K. pneumoniae. Moderate efficacy was observed for Piperacillin, Cefepime, Meropenem, and Levofloxacin, with sensitivity levels around 70% and more pronounced variability depending on the sample type. Meanwhile, Nitrofurantoin, Cefazolin, Trimethoprim, and Tobramycin exhibited low sensitivity rates (less than 60%) and high resistance levels, limiting their clinical use in treating infections caused by K. pneumoniae. The results of the sensitivity analysis of Klebsiella pneumoniae isolated from various biological materials reveal both general patterns and significant differences in antibiotic resistance mechanisms.

In the study by *Levchenko et al.,* based on a regional microbiological monitoring system, isolates from respiratory samples (sputum, bronchial aspirate) showed higher resistance to colistin and carbapenems compared to urine samples. The authors attribute this to systemic antibiotic therapy in patients with pneumonia [15].

Gizatullina et al. found that strains from wound exudates demonstrated aminoglycoside resistance in 80% of cases, while urinary isolates showed resistance in only 50%. This highlights the need for individualized therapy depending on the infection site [6].

Trizna and colleagues emphasize the high multidrug resistance of strains from postoperative wounds, pointing to the risk of superinfections in surgical departments [18].

The study by Kataeva et al. shows significant differences in resistance patterns in the lower respiratory tract of patients with community-acquired pneumonia, especially in COVID-19 cases. The prevalence of carbapenem-resistant K. pneumoniae strains reached 70% [11].

Finally, the work of *Yarets and Shevchenko* underscores the importance of local microbiological monitoring, demonstrating the dependence of sensitivity on hospitalization timing and sample collection conditions [21].

Gordinskaya et al. investigated the molecular-genetic mechanisms of resistance in Klebsiella pneumoniae isolates from hospitals in Nizhny Novgorod. They found that strains from the urogenital tract and sputum exhibited a high frequency of resistance to third-generation cephalosporins and carbapenems. This resistance was linked to the presence of plasmid genes bla_KPC and bla_OXA-48-like, highlighting the importance of molecular monitoring in clinical practice [7].

Antonova and Zhiltsov discussed the challenges of antibacterial therapy for hospital-acquired infections caused by carbapenemase-producing K. pneumoniae strains. The most resistant isolates were obtained from wounds and catheters. Combined therapy using colistin and tigecycline was recommended [1].

Beloborodov et al. emphasized the necessity of accurate sampling and identification of the infection site to select appropriate antibiotics. According to the "Sepsis Forum" guidelines, infections of the bloodstream or abdominal cavity caused by multidrug-resistant K. pneumoniae strains require parenteral administration of carbapenems and colistin [2].

Mamchik et al. studied K. pneumoniae strains isolated from wound exudates. These strains showed high resistance to fluoroquinolones, aminoglycosides, and even meropenem. Treatment escalation tactics were determined based on the infection site and clinical course [15].

Yakovlev and Suvorova focused on urinary tract infections. In urine samples from catheterized patients, a high prevalence of ESBL-producing K. pneumoniae strains was detected, underscoring the need for UTI prevention in catheterized patients [20].

Kozlova and Barantsevich analyzed K. pneumoniae strains isolated from wounds, blood, and respiratory tracts. The highest resistance was found in blood isolates (up to 70% resistance to cefepime and imipenem), reflecting the need for enhanced diagnostics and patient isolation [13].

A study by *Nirwati et al.* in Indonesia demonstrated a high level of antibiotic resistance and biofilm-forming ability in K. pneumoniae isolates primarily from respiratory samples (51.5%) and purulent discharges (16.2%). Approximately 54.5% of strains met the criteria for multidrug resistance, and 85.6% were capable of forming biofilms of varying intensity. Notably, biofilm-forming strains showed increased resistance to most antibiotics except meropenem, amikacin, and piperacillin-tazobactam. These findings highlight the importance of considering biofilm formation when isolating K. pneumoniae from sputum, aspirates, or purulent materials, as it is a key factor in therapy resistance and should influence antimicrobial regimen selection and treatment duration [24].

As *Navon-Venezia, Kondratyeva, and Carattoli* emphasize, Klebsiella pneumoniae is not only one of the most resistant Gram-negative pathogens but also a global "gateway" and vector for the transmission of antibiotic resistance genes. The authors highlight K. pneumoniae's role in the emergence of the "super-resistome" phenomenon, where strains simultaneously carry multiple β-lactamases (including KPC, OXA-48, and NDM-1), as well as aminoglycoside and fluoroquinolone resistance genes on mobile plasmids. Importantly, many of these genes are found in epidemiologically successful clones (ST258, ST11, ST147), which are capable of rapid intercontinental spread and are associated with hospital outbreaks. These data complement our analysis, indicating that strains isolated from blood and invasive sites are more likely to possess multiple resistance mechanisms than those from superficial samples, which is critical when choosing empirical therapy [23].

The study by *Ballén et al.* found that K. pneumoniae strains isolated from urine exhibited the highest antibiotic resistance at 64.91%, surpassing even blood (63.64%) and respiratory (51.35%) isolates. These uropathogenic strains also showed high ESBL (extended-spectrum β-lactamase) production and statistically significant resistance to fosfomycin (24.56%; p = 0.008). Moreover, nearly half (46.1%) of all biofilm-forming isolates were recovered from urine. This emphasizes that uropathogenic K. pneumoniae strains can combine antibiotic resistance, increased virulence, and biofilm formation, complicating treatment especially in patients with catheters or chronic UTIs. The authors stress the need for active monitoring not only of resistance but also of virulence factors such as the uge, rmpA, and iucA genes, which contribute to bacterial invasion and immune evasion [22].

These data confirm the key hypothesis: K. pneumoniae sensitivity strongly depends on the source of the biological material and the clinical context. Therefore, a standardized treatment approach is insufficient; a personalized antimicrobial strategy based on local data is necessary.

The highest resistance to β-lactams, carbapenems, and fluoroquinolones was observed in isolates from blood, sputum, tracheal aspirates, and wound exudates. Urine isolates also showed high resistance, particularly in cases of prolonged catheterization, often accompanied by biofilm formation and ESBL production, making them potential reservoirs for hospital transmission of resistance.

Recent studies also demonstrate that K. pneumoniae strains isolated from invasive sources more frequently carry multidrug resistance genes, including bla_KPC, bla_NDM, bla_OXA-48-like, as well as plasmids encoding resistance to amikacin and colistin. These findings underscore the necessity of molecular typing and local resistance monitoring.

Conclusion

Thus, the obtained data highlight the need for regular monitoring of antibiotic resistance and the rational selection of antibacterial therapy based on the sensitivity of specific strains and the type of infected biological material. This is especially relevant in the context of increasing antibiotic resistance and a limited arsenal of effective drugs.

The conducted analysis showed that Klebsiella pneumoniae remains one of the most significant and dangerous hospital pathogens due to its high frequency of antibiotic resistance, ability to form biofilms, and broad spectrum of virulence factors. The resistance of K. pneumoniae strains varies depending on the source of the biological material, which is influenced both by the physiological characteristics of the infection site and local antibiotic therapy.

Future research should focus on integrating molecular data with clinical observations to enable timely identification and containment of epidemiologically significant clones of K. pneumoniae.

Study Limitations: *The single-center nature of the study may limit its generalizability, and the absence of long-term follow-up data restricts the assessment of post-discharge outcomes.*

Author Contributions*: All authors contributed equally to the writing of this manuscript.*

Conflict of Interest: *The authors declare no conflicts of interest. This material has not been submitted to other journals and is not under consideration elsewhere.*

Funding: *No funding was received for this study.*

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